Critical dynamics in population vaccinating behavior

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Vaccine refusal can lead to renewed outbreaks of previously eliminated diseases and even delay global eradication. Vaccinating decisions exemplify a complex, coupled system where vaccinating behavior and disease dynamics influence one another. Such systems often exhibit critical phenomena—special dynamics close to a tipping point leading to a new dynamical regime. For instance, critical slowing down (declining rate of recovery from small perturbations) may emerge as a tipping point is approached. Here, we collected and geocoded tweets about measles–mumps–rubella vaccine and classified their sentiment using machine-learning algorithms. We also extracted data on measles-related Google searches. We find critical slowing down in the data at the level of California and the United States in the years before and after the 2014–2015 Disneyland, California measles outbreak. Critical slowing down starts growing appreciably several years before the Disneyland outbreak as vaccine uptake declines and the population approaches the tipping point. However, due to the adaptive nature of coupled behavior–disease systems, the population responds to the outbreak by moving away from the tipping point, causing "critical speeding up" whereby resilience to perturbations increases. A mathematical model of measles transmission and vaccine sentiment predicts the same qualitative patterns in the neighborhood of a tipping point to greatly reduced vaccine uptake and large epidemics. These results support the hypothesis that population vaccinating behavior near the disease elimination threshold is a critical phenomenon. Developing new analytical tools to detect these patterns in digital social data might help us identify populations at heightened risk of widespread vaccine refusal.

socioecological systems | machine learning | early warning signals | online social media | vaccine refusal

In recent decades, vaccine refusal has contributed to the resurgence of measles and pertussis and significantly delayed the global eradication of polio (1, 2). For instance, the 2014–2015 measles outbreak in Disneyland, California was preceded by declining kindergarten measles–mumps–rubella (MMR) vaccine coverage in California between 2010 and 2014 (3) (Fig. 1*A*). Vaccine compliance at school entry fell to 70–90% in many cases and sometimes even lower in some Los Angeles schools (3). Inadequate vaccine compliance appears to have played a role in the outbreak (4), contributing to a significant peak in California measles case notifications in late 2014 and early 2015 (5) (Fig. 1*A*). The outbreak garnered significant public interest, causing a large spike in both US-geocoded tweets regarding measles (Fig. 1*B*) and Google Internet searches in California for "MMR" and "measles" (Fig. 1*C*) as reports of cases began to flow in. Amid the resulting public outcry, the California legislature began taking steps to disallow nonmedical exemptions (6–8), although statewide MMR vaccine uptake began to recover before these policy changes went into effect (3) (Fig. 1*A*).

The changes in vaccinating behavior before and after the Disneyland measles outbreak are consistent with a coupled behavior–disease dynamic in which vaccinating decisions and disease dynamics influence one another in a nonlinear feedback loop. The mathematical modeling of coupled behavior–disease dynamics is growing rapidly (9–12), although relatively little attention has been devoted to critical phenomena in such systems. The theory of critical transitions (tipping points) and their early warning signals may help public health officials anticipate when and where resistance to vaccination might develop and intensify. A critical transition occurs when a complex system shifts abruptly to a strongly contrasting state as an external driver moves the system past a bifurcation point (13, 14). These shifts may exhibit characteristic early warning signals as a consequence of critical slowing down (CSD), in which a declining rate of recovery from small perturbations causes dynamics to become more variable. CSD can be detected by changes in indicators such the variance, lag-1 autocorrelation (AC), and coefficient of variation in high-resolution time series of state variables (13, 14).

Social norms tend to reinforce currently accepted behavior and thus promote status quo practices in populations (15–17). However, individuals also make vaccinating decisions based on the perceived risks of the vaccine and the diseases they prevent (15). Here, we hypothesize that coupled behavior–disease systems exhibit a tipping point arising from interactions between social norms, perceived vaccine risk, and perceived disease risks. Specifically, we investigate the effects of risk perception in terms of the ratio of the magnitude of perceived vaccine risk to the magnitude of perceived risk of disease complications (we will call this "relative vaccine risk" for short). Rising public concern about potential vaccine complications can cause the relative vaccine risk to grow to a tipping point where social norms in support of a status quo of high vaccine acceptance can no longer prevent a drop in provaccine sentiment. If the population moves beyond this tipping point, a decline in provaccine sentiment causes fewer people to seek vaccination and herd immunity breaks down, enabling outbreaks of various sizes. However,

Significance

Complex adaptive systems exhibit characteristic dynamics near tipping points such as critical slowing down (declining resilience to perturbations). We studied Twitter and Google search data about measles from California and the United States before and after the 2014–2015 Disneyland, California measles outbreak. We find critical slowing down starting a few years before the outbreak. However, population response to the outbreak causes resilience to increase afterward. A mathematical model of measles transmission and population vaccine sentiment predicts the same patterns. Crucially, critical slowing down begins long before a system actually reaches a tipping point. Thus, it may be possible to develop analytical tools to detect populations at heightened risk of a future episode of widespread vaccine refusal.

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